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Final Report

INSTRUMENTATION FOR THE CHARACTERIZATION OF THE MICROWAVE PROPERTIES AT 18, 35 and 94 GHz

AD-A199 741

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The Earth Resources Millimeter-Wave Radar (ERMIR) has been developed to characterize the microwave properties of Earth scenes at 18, 35, and 94 GHz. This instrument operates in either the continuous-wave or frequency-modulated continuous-wave modes and may be used to measure reflectivity, transmissivity, backscatter, and bistatic scattering. The development and construction of this instrument was guided by the need to acquire these parameters in situ and in remote locations.

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PREFACE

The work presented here is the final report for Contract No. N00014-81-C-0692, Modification No. P00011, entitled "Instrumentation for the Field Measurement of Dielectric Constant at 18, 35 and 94 GHz". The principal investigators for this project were Dr. Robert G. Onstott and Mr. Richard W. Larson. The National Aeronautics and Space Administration (NASA) technical monitors for this program were Drs. Kenneth C. Jezek and Robert H. Thomas.

This program was concurrently supported by the United States Geological Survey (USGS), Contract No. 14-08-0001-22074, entitled "Development of Instrumentation for the Field Measurement of Dielectric Constant". The USGS provided the funds for the addition of the 18 GHz instrumentation. The USGS technical monitor was Dr. Edward Josberger.

ACKNOWLEDGEMENTS

We would like to thank the many people who have contributed to the design and fabrication of the Earth Resources Millimeter-Wave Radar. We would especially like to thank A. Fromm for his contribution.

This work was also funded by Environmental Research Institute of Michigan Internal Research and Development Account 645414 and Capital Equipment Funding.

1. EXECUTIVE SUMMARY

1.1 Overall Project Summary

The objective of this work was the development of instrumentation that contributes to a better understanding of the millimeter-wave properties of the many Earth scenes. This sensor was to be versatile and allow us to acquire data which contributes to a variety of aspects important to remote sensing science and applications. The Earth Resources Millimeter-Wave Radar (ERMIR) has the flexibility to allow *in situ* and laboratory measurement of many of the microwave properties which are important in the characterization of a scene. For example, the measurement of dielectric properties, of monostatic scattering properties, and of bistatic scattering properties is possible. As an example, the determination of *in situ* dielectric properties are important quantities in the effective interpretation of data obtained by ground, aircraft, and spacecraft remote sensing instruments and in modeling electromagnetic scattering from natural scenes. Given the variety of present and future sensors as shown in Table 1, it is important to be able to fully characterize the electromagnetic properties of a scene over a wide range of wavelengths in the microwave and millimeter wave region.

The system includes: (a) instrumentation that operates at wavelengths of 3 mm (94 GHz), 9 mm (35 GHz), and 17 mm (18 GHz); (b) a structure for establishing the variation of the measurement geometry; (c) field power supplies; and (d) a data acquisition system. In this effort, NASA supported the development of the 35 GHz and 94 GHz capability, and the USGS supported the development of the 18 GHz channel. A primary goal was to combine these three sensors into a single instrument. A third activity supported with ERIM IR&D funding focused on the refinement and development of instrumentation for use in the field and the laboratory for the measurement of permittivities in the frequency range from 0.1 GHz to 10.0 GHz.

The ERMIR has been active; it has already participated in a variety of investigations. These include the study of sea ice and snow in the marginal ice zone (MIZEX '87), the backscatter from water (ONR URI), the

microwave properties of artificial sea ice (CRRELEX '88), and a pilot study of the microwave properties of snow (USGS Rabbit Ears Pass Experiment, '88).

Table 1
Microwave Remote Sensing Instruments

Instrument	Operating Frequency (GHz)
Aircraft	
NADC-ERIM-P3 SAR, active	1.25, 5.3, 9.35
USN-NRL-P3, passive	19, 22, 31, 37, 90
NASA-CV-990, passive	18, 21, 37, 90
CCRS-IRIS SAR, active	5.3
INTERA STAR-1 SAR, active	9.4
INTERA STAR-2 SAR, active	9.4
Spaceborne Spacecraft	
SMMR, passive	6.6, 10.7, 18, 21, 37
SSM/I, passive	19.3, 22.2, 37, 85.5
Proposed Instruments	
SIR-C (SAR)	1.25, 5.3, 9.6
ERS-1(SAR)	5.3
NROSS-2 (SAR & SCATT)	TBD
RADARSAT (SAR & SCATT)	5.3, 14
J-ERS-1(SAR)	5.3
EOS (SAR & SCATT)	TBD

1.2 The 18, 35, AND 94 GHz Millimeter-Wave Sensor

This sensor operates at 18, 35, and 94 GHz. A block diagram showing major system components is provided in Figure 1. The following measurement procedures are accommodated:

(1) Monostatic and bistatic reflection coefficients;

(2) Monostatic and bistatic transmission loss; and

(3) Monostatic and bistatic scattering coefficients.

The sensor is comprised of a transmitter/receiver unit (TRU), a transmitter/calibration unit (TCU), an electronics and control unit (ECU), a data acquisition system, and a mounting structure. The TRU includes three sets of millimeter-wave sources and assorted hardware (mixers, video amplifiers, detectors, intermediate filtering networks, and three pairs of transmitting and receiving antennas) which may be operated in a frequency-modulated continuous-wave (FM-CW) mode or in a continuous-wave (CW) mode. A simplified block diagram representative of each of the three frequency bands in the TRU is shown in Figure 2. When used alone, this unit operates in the FM-CW scatterometer mode. Figure 3 shows this system operating from a sled during the USGS-sponsored Rabbit Ear '88 study of the microwave properties of snow. A specification table for the ERMIR when operated in this mode is provided in Table 2.

The ECU houses the control electronics, digital displays, and power sources. The system may be supplied power using either a 115 VAC gas-powered generator or a pack containing 12 VDC deep-cycle rechargeable batteries.

The TCU is comprised of three transmitters. These are used in conjunction with receivers in the TRU for implementation of the bistatic and transmission loss modes of operation. Bistatic measurements may be made over a range of angles from 10 to 80 degrees. They may be aligned so that reflection and transmission coefficients at VV and HH polarization are measured. The bistatic and reflectometer measurement and transmission measurement configurations are illustrated in Figures 4 and 5, respectively. Note that the transmitters and receivers are separated and positioned so that they view each other directly or are

focused on the ground path to be characterized.

A battery-powered data acquisition system functions independently of the instrumentation control electronics. Data recording is accomplished by the integration of a compact Campbell 21X micrologger. These data are stored on magnetic tape for later transfer to a microcomputer.

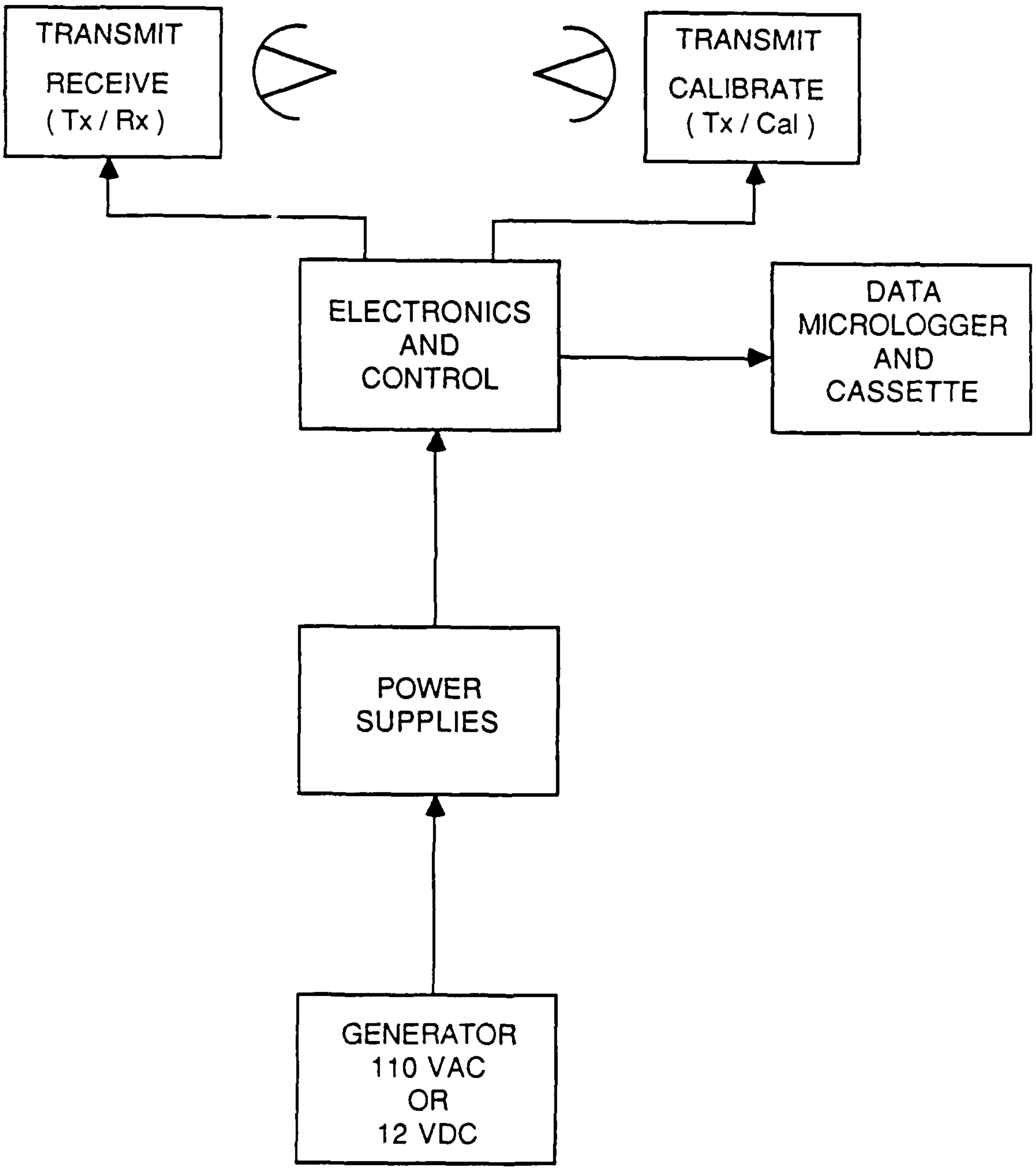


Figure 1. Millimeter-Wave Measurement System Block Diagram

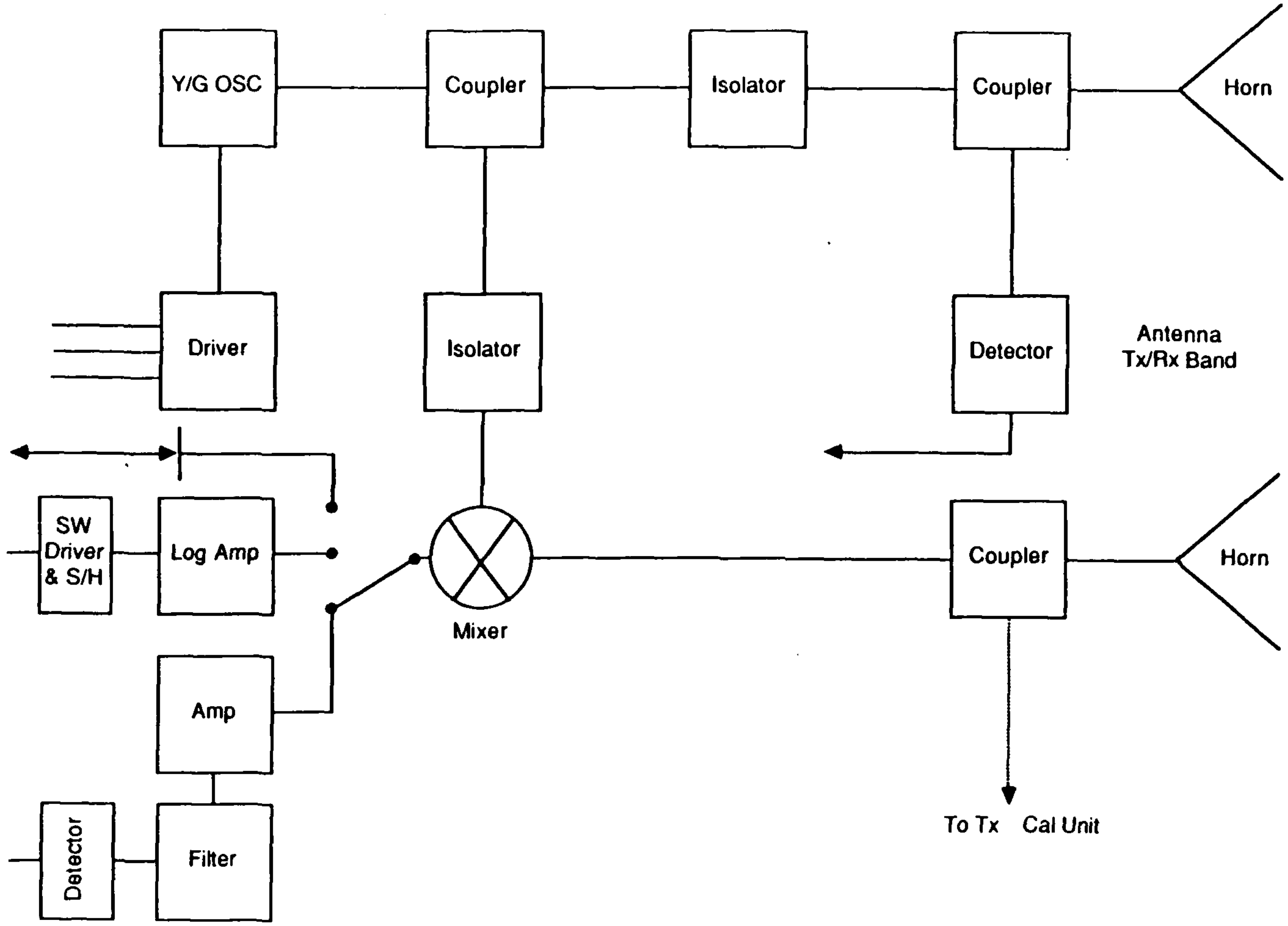


Figure 2. RF and IF Block Diagram for 18, 35, and 94 GHz Radar

Figure 3. Millimeter-Wave Observations Acquired Using ERMIR During Rabbit Ears '88

Table 2
Shipscat Specifications

Type	FM-CW		
Frequency (GHz)	18	35	94
FM Sweep (MHz)	1000	1100	400
Antenna Beamwidth (°)	5	3.5	3
Polarizations[1]	V or H	V or H	V or H
Height (m)	16	16	16
Footprint[2] (m)	2.0	1.4	1.2
N-Freq[3]	9	6	6
N-Spatial[4]	13	9	30
N-Total[5]	117	54	180
σ ° Precision (dB)	± 0.6	± 1.0	± 0.5

[1] V = VV, H = HH, X = VH or HV
[2] Footprint at 40 ° (Except for 0.5 GHz)
[3] Number of Independent Samples Via Excess Bandwidth
[4] Independent Samples per Spatial Footprint
[5] Total Number of Independent Samples per Footprint

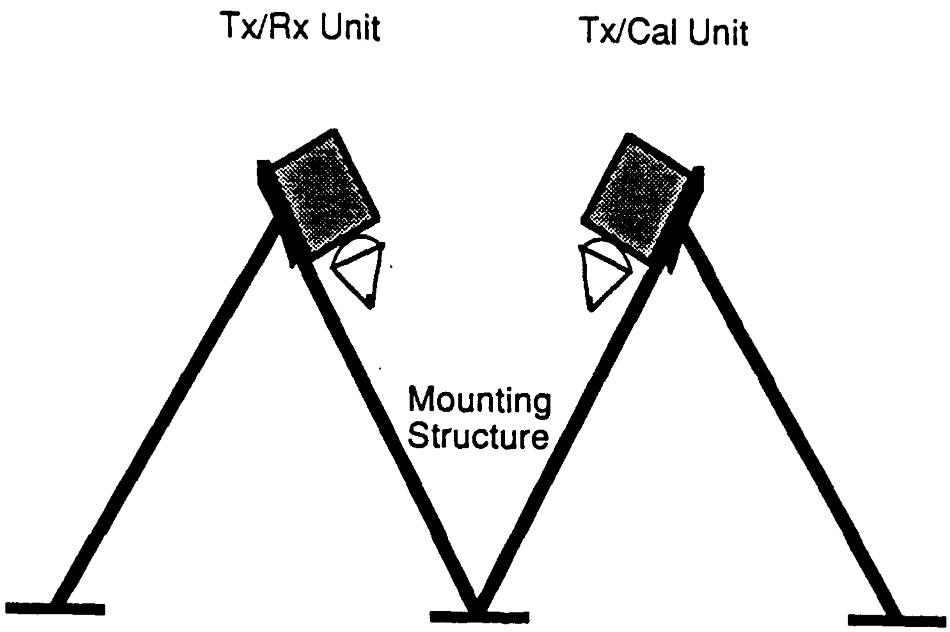


Figure 4. Bistatic and Reflectometer Measurement Configuration

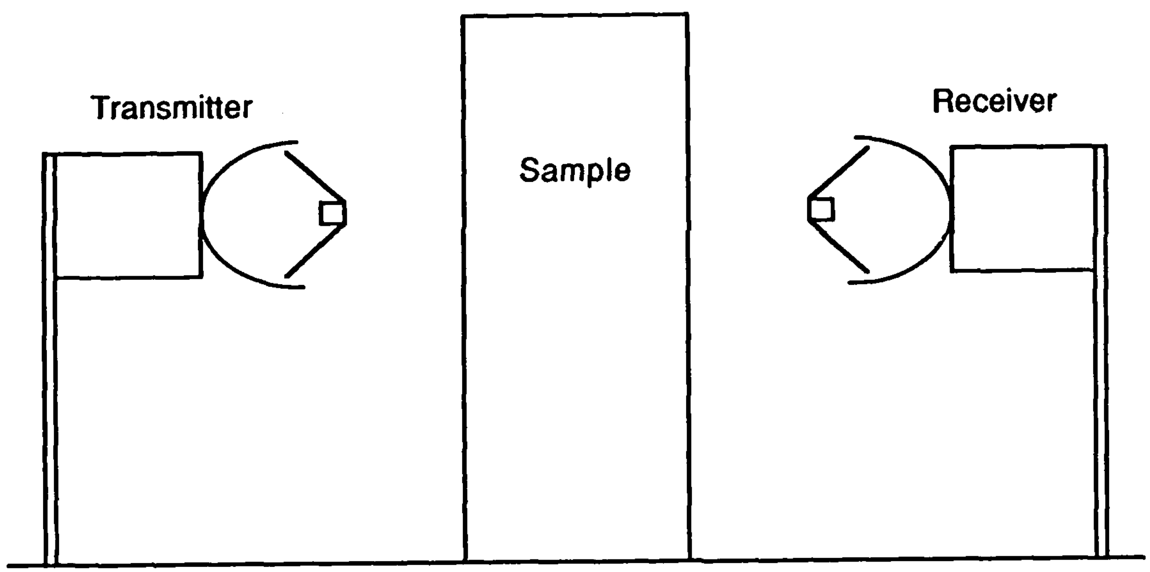


Figure 5. Transmission Measurement Configuration

1.3 Discussion of Measurements Methods

The characterization of a scene's electromagnetic properties at millimeter wave frequencies is accomplished using either reflectometer or transmission techniques. For example, measurement of the bistatic reflection coefficient allows the estimate of the magnitude of the dielectric constant. At the lower microwave frequencies where wavelengths are much longer, cavity and transmission line techniques may also be used. Data would be obtained at a variety of incidence angles so that scattering losses due to rough surfaces may be determined and accounted for in the inversion process.

1.3.1 Bistatic Measurements

The received signal power P_R is given by the equation

$$P_R = \frac{P_T G_T G_R \lambda_o^2 H_R}{(4\pi)^3 R^4} |R(\theta)|^2 \tag{1}$$

where P_T = power transmitted,
G_T = transmitter antenna gain,
G_R = receiver antenna gain,
λ_o = wavelength in free space,
H_R = receiver gain function,
R = range,
θ = incidence angle,and
$R(\theta)$ = Fresnel reflection coefficient.

The reflection coefficient is polarization dependent and is given by

$$R_H(\theta) = \frac{\cos\theta - \left[\epsilon_r^* - \sin^2\theta\right]^{1/2}}{\cos\theta + \left[\epsilon_r^* - \sin^2\theta\right]^{1/2}} \tag{2a}$$

$$R_V(\theta) = \frac{\epsilon_r^* \cos\theta - \left[\epsilon_r^* - \sin^2\theta\right]^{1/2}}{\epsilon_r^* \cos\theta + \left[\epsilon_r^* - \sin^2\theta\right]^{1/2}} \tag{2b}$$

where $R_H(\theta)$ = Fresnel reflection coefficient for horizontal polarization,

and $R_V(\theta)$ = Fresnel reflection coefficient for vertical polarization,

ϵ_r^* = complex relative dielectric constant.

If system parameters are constant during a given measurement series, then

$$P_T \frac{G_T G_R \lambda_o^2 H_R}{(4\pi)^3 R^4} = K, \text{ and} \tag{3a}$$

$$P_R = K \; |R(\theta)|^2. \tag{3b}$$

Using data from measurements taken at several incidence angles, Eqs. 2 and 3 can be used to compute values of ϵ_r^*. Because ϵ_r^* is independent of θ, these values can be averaged to give a mean dielectric constant. Corrections to measured values of $R(\theta)$ for surface roughness effects can be made by using a suitable model. The system function K is determined, after the measurement series, by placing a flat metal plate with a reflection coefficient of 1 over the reflecting area and by adjusting the receiver for maximum received signal power. It can be seen from Eqs. 3a and 3b that $K = P_R$. Data may be obtained at both horizontal and vertical polarization. Brewster angle effects may also be observed when using vertical polarization. Measurements made at steep angles will be less sensitive to angle measurement errors; hence, they provide the most accurate data to be used in the estimate of the dielectric constant.

Measurement precision is verified by using solid and liquid reference materials which have known dielectric properties. For

because their dielectric properties are relatively frequency independent and cover a wide range of values. A list of currently selected reference dielectric materials are presented in Table 3. These materials have different physical properties and allow the study of precision and repeatability as a function of structural characteristics.

1.3.2 Transmission Measurements

Measurement of the attenuation properties of a sample material completes the description of the complex dielectric properties of the scene. This is accomplished by aligning the TRU with the TCU as shown in Figure 5. A sample material is placed between the transmit and receive antennas. In the case of snow, adjacent snow pits may be dug and aligned transmit (TCU) and receive (TRU) units may be positioned vertically so that a loss profile is measured. The power received with the dielectric material in place is compared with that received when the material is replaced by free space. The loss attributed to the sample may then be calculated. Additional measurements may be made in which the thickness of the sample is varied. This is especially important when the material is low loss; multiple reflections within the dielectric slab become significant and effect the accuracy of the measurement.

TABLE 3

SELECTED REFERENCE DIELECTRIC MATERIALS

Material	Phase	Dielectric Constant	
		Real Part	Loss Tangent
Carbon Tetrachloride	Liquid	2.17	0.00008
Benzene	Liquid	2.28	0.0005
Teflon	Solid	2.09	0.00014
2-Propanol	Liquid	3.73	0.79
Paraffin Wax	Solid	2.25	0.0004
Polystyrene	Solid	2.48	0.0012
Stycast Sheets	Solid	3 - 30	0.002
Ethanol	Liquid	4.54	0.49
1-Octanol	Liquid	2.87	0.24
Dry Sand	Solid	2.59	0.013
NaCl Crystals	Solid	5.91	0.0002
1-Butanol	Liquid	3.70	0.53

Loss values can be used to calculate the loss tangent, tan δ, using the relationship

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\epsilon_r'}{2} \left(\sqrt{(1 + \tan^2\delta)^2} - 1 \right)} \tag{4}$$

where the value of α, in nepers/meter is derived from the attenuation measurements and ϵ_r' is the real part of the complex dielectric constant.

The dielectric constant can be obtained from the transmission measurement if the propagation time can be accurately measured. The propagation time can be measured to achieve a spatial resolution of 7.5 cm using an FM system over a 2 GHz frequency bandwidth. This approach is practical for situations where low loss-tangent values are encountered, such as very cold conditions in ice or snow.

1.3.3 Measurement of Monostatic and Bistatic Scattering Coefficients

Measurement of the monostatic scattering coefficients $\sigma°$ allow the empirical and theoretical study of the active microwave behavior of the Earth's surface. These data also assist in the interpretation of aircraft and satellite measurements and in the development of a radar data base. The backscattering coefficient may be measured as a function of frequency, incidence angle, polarization, and aspect angle. Note that backscatter is a special bistatic-scattering case in which the incident-field and the scattered-field incidence and azimuth angles are identical.

The bistatic scattering coefficient $\sigma°$ may be measured as a function of both transmit and receive incidence and azimuth angles. These data are important in the study of bistatic scattering and in the advanced stages of studies where active and passive microwave data, scene characterizations, and theoretical model predictions are to be thoroughly intercompared. Emission may be predicted based upon the empirical measurement of the bistatic scattering cross-section; these predictions may then be compared with actual measurements and model predictions.

1.4 INVESTIGATIONS

1.4.1 MIZEX '87

The Winter Marginal Ice Zone Experiment (MIZEX '87) was the first investigation in which this system participated. An important program goal was to better describe the ice-ocean-atmosphere processes responsible for the advance of the ice edge during winter and the effect on acoustic and electromagnetic properties. This investigation was conducted in Fram Strait (the region between Greenland and Spitzbergen). Synthetic aperture radar (SAR) coverage was provided during this investigation and used daily in planning ship activities. Intensive ice sampling was done from the ship to describe ice types and physical properties. In addition, passive microwave observations were made at 6, 10, 18, 35, and 94 GHz. The ERMIR was operated from an ice strengthened ship (see Figure 6) in its monostatic mode. Backscatter measurements were made of sea ice, snow, and open water. Ice types included multiyear, first-year, frazil, grease, and pancake. Angular response measurements were made with the ship at station next to ice floes. Measurements were also made as the ship traversed through extensive regions of new ice and ocean eddies. Data representative of that collected during this activity are provided in Figures 7 and 8. In examining these data at 18 and 35 GHz, it is easy to recognize the need for an instrument which has a wide operating range and the ability to measure very small cross sections. The water between the ice floes in the marginal ice zone was exceedingly smooth reflecting most all of the incident energy into the forward direction. An important aspect of this system is the ability to collect multiple frequency data coincidently; thereby improving the ability to study the frequency behavior of features of interest.

1.4.2 Laboratory-Based Ship Wake Study

An investigation is underway which is sponsored by an ONR-funded University Research Initiative (URI) Program for Ship Hydrodynamics. This is a multi-disciplinary research program which concentrates on four main areas:

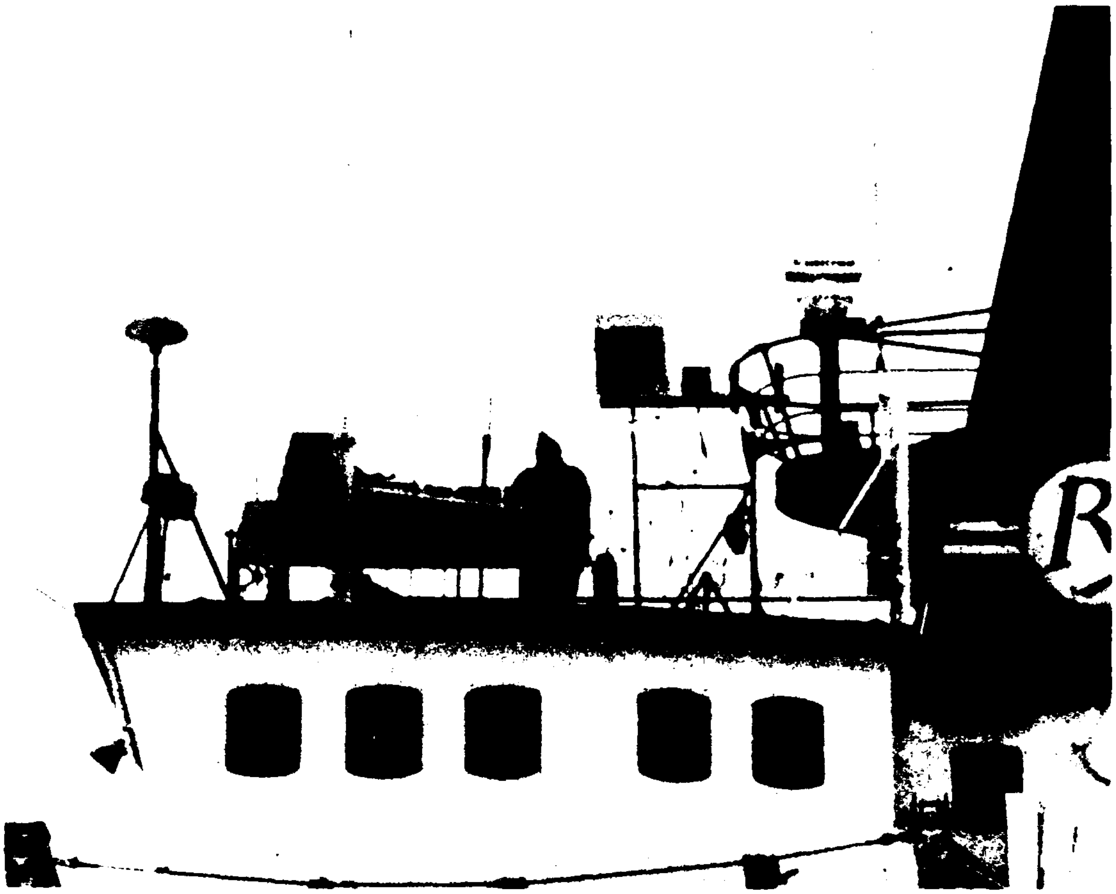


Figure 6. Ship-Based Scatterometer

Data Acquired Using the Scatterometer Mounted Atop the Wheelhouse of an Ice Stengthened Ship.

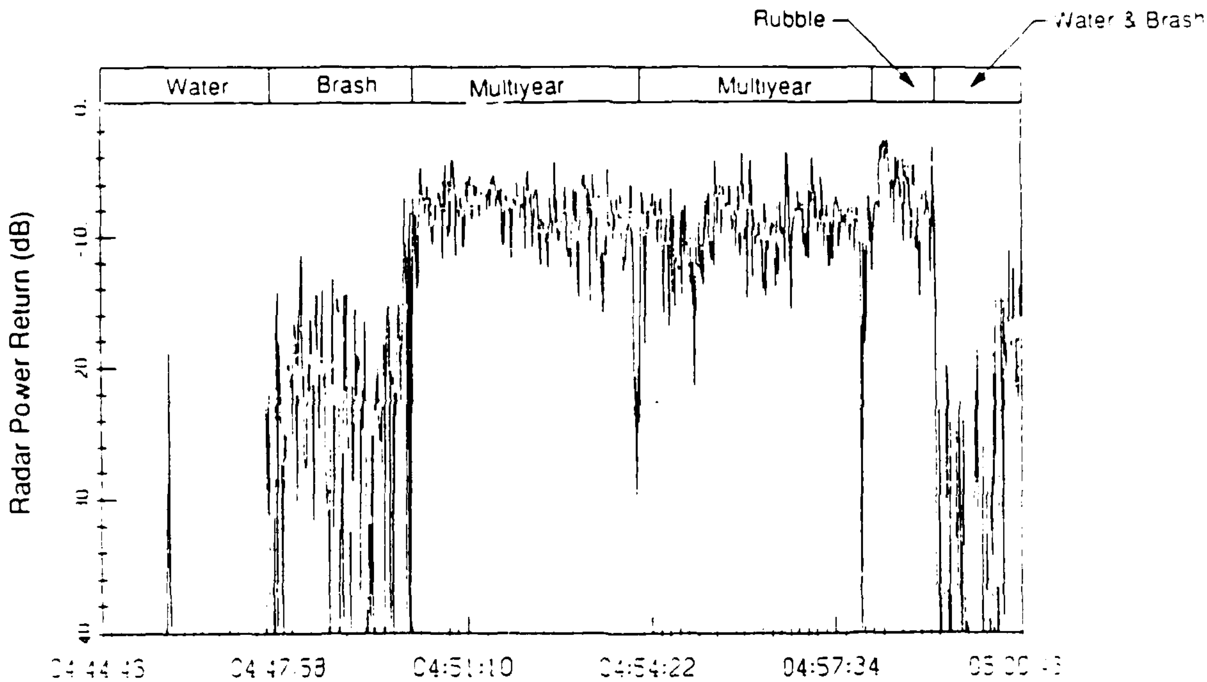


Figure 7. Radar Backscatter Cross-Section at 18 GHz, VV-Polarization, and a 40 Degree Incidence Angle

Data Acquired Using the Scatterometer Mounted Atop the Wheelhouse of an Ice Stengthened Ship.

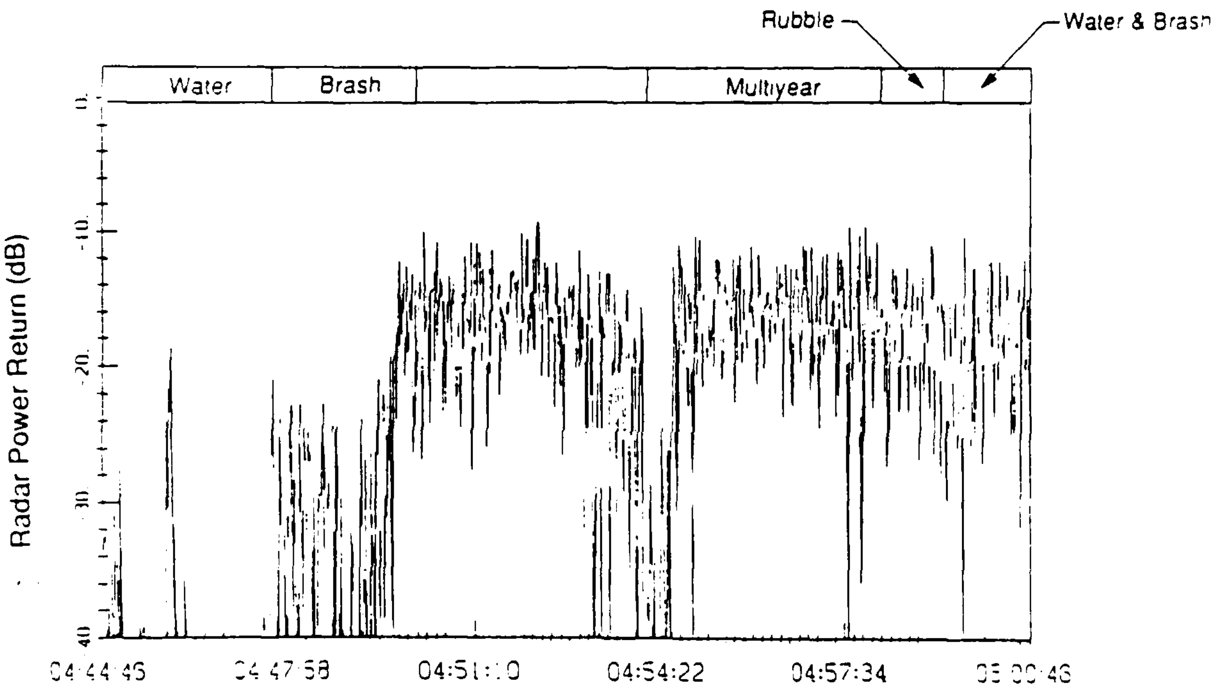


Figure 8. Radar Backscatter Cross-Section at 35 GHz, VV-Polarization, and a 40 Degree Incidence Angle

(1) Non-Acoustic Remote Sensing;

(2) Viscous Boundary Layer and Wake Flows;

(3) Free Surface Flows; and

(4) Bubbles, Cavitation, and Noise.

The goal of the microwave measurements is to better understand the hydrodynamic mechanism which will improve our ability to sense ship generated disturbances. Experiments will be performed to correlate the hydrodynamic properties of the flow field with scene microwave properties.

Because of the ability to operate in both bistatic and monostatic modes at millimeter frequencies, this instrument has the potential to uniquely contribute to the description of the sea surface. Visual observations of reflected sunlight near the specular direction appear to be very sensitive to small perturbations of surface roughness. The forward scattering properties of the water surface may be exploited using the bistatic mode. Secondly, the amount of energy which is backscattered from the ocean surface is small compared to that which is forward scattered. Thus, the higher signal levels of the forward scattered energy is anticipated to permit an improved measurement of very small amplitude waves. The experimental approach consists of making a series of conventional monostatic radar backscatter measurements of controlled waves and known surface hydrodynamics in a model towing tank at 18, 35, and 94 GHz. These measurements will be examined to determine the optimum frequency/polarization combination for bistatic measurements and in evaluating ocean-wave scattering models. The monostatic measurement sequence will be repeated using the bistatic configuration. The bistatic measurements will then be used to determine the preferred imaging geometry for the examination of different ship wake components.

1.4.3 CRRELEX '88

The ERMIR was utilized in the laboratory-based study of artificially grown sea ice known as CRRELEX. In this investigation a series of active microwave measurements are being studied in conjunction with

passive microwave measurements and detailed ice physics. The overall objective of this program is to produce a more complete understanding of the parameters and processes which effect the microwave signatures of Arctic sea ice. In pursuing these goals, the ability to make microwave measurements of artificially grown sea ice in a laboratory environment was developed at U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). A conclusion reached through discussion with both theoretical modelers and experimentalists is the need to coordinate very detailed laboratory-like measurement investigations in which the physical properties that need to be measured to validate the developing models are measured, and that those developing models are fully aware of the constraints of what can be measured. During this investigation, critical electromagnetic characterization data were identified and monitored continuously throughout the experiment series.

Measurements with the 18, 35, and 94 GHz sensor were coordinated with fully polarimetric measurements at 1.75, 5, and 10 GHz and passive microwave measurements from 6, 10, 18, 35, and 94 GHz.

1.4.4 Rabbit Ears Pass Snow Experiment of 1988

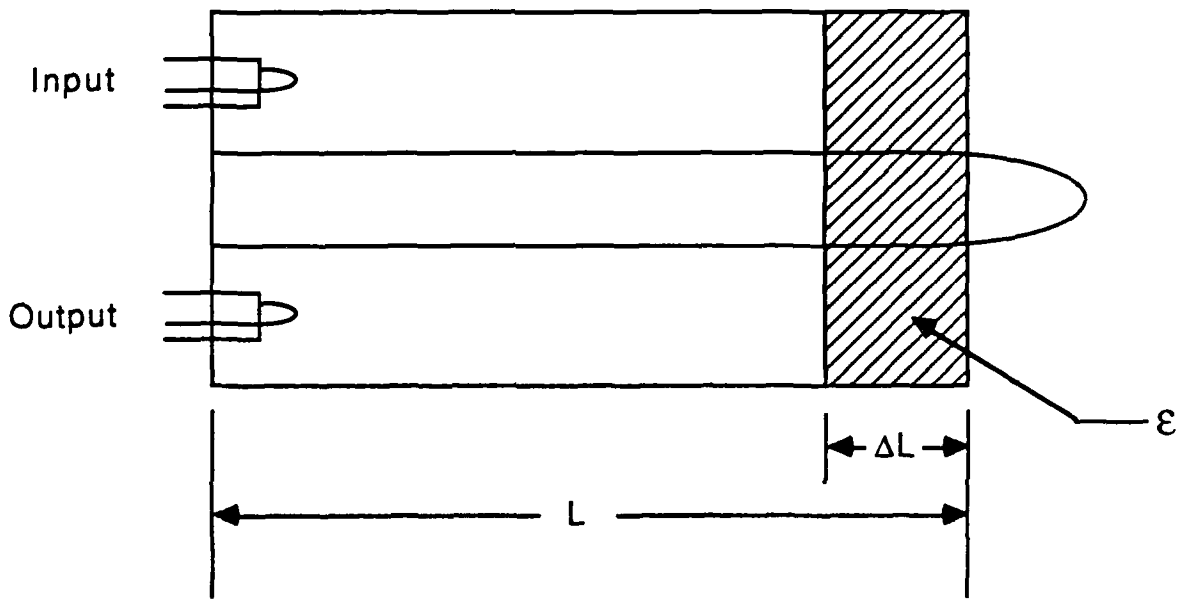
A coordinated study of the microwave properties of snow at 18, 35, and 94 GHz and the physical properties of snow was conducted during March 1988 at Rabbit Ears Pass located in the Colorado Rockies. These measurements were made in conjunction with NASA aircraft overflights which were conducted over this experiment site.

Snowpack depth ranged from 190 to 200 cm. Size of the fine grained snow crystals ranged from 0.25 to 1.0 mm throughout the snowpack. Density of the dry cold snow was about 0.12 to 0.20 gm/cc. The sensor was operated in the scatterometer mode and mounted to a sled. This system was transported about a course 70 meters in length. Snowpit data were acquired. Backscatter data were recorded as a function of position along a 100 m long course at eight incidence angles between 0 and 70 degrees.

Snow characterization measurements and logistics were coordinated by Dr. Ed Josberger of the USGS/Tacoma.

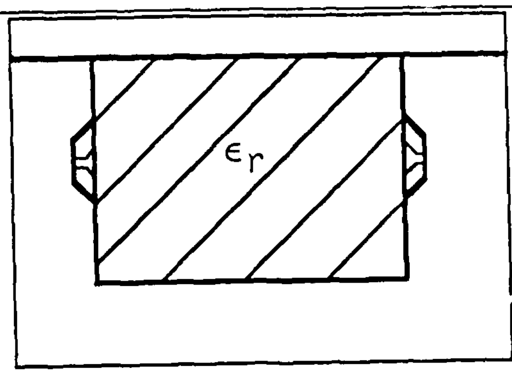
1.5 Additional Portable Dielectric Instrumentation

A concurrent ERIM-funded research effort in dielectric instrumentation has focused on the refinement and fabrication of a versatile, lightweight, portable dielectric unit (PDU). Based upon previously constructed and field-tested devices, this new unit utilizes several previously verified measurement techniques and represents an improvement in both operational capabilities and packaging. A compact unit has been fabricated which allows for the measurement of complex permittivity using several in situ probes. Selection of the correct probe is based upon the physical characteristics of the material and frequency range of interest. The rechargeable instrument is capable of measuring dielectric constant within an extremely broad frequency band of 300 MHz to 8.0 GHz. Low to mid frequency values are obtained from the use of coaxial resonators and circular cavities as shown in Figures 9 and 10. The shift in resonant frequency relates to the real part of the dielectric constant while the change in the Q of the resonator is indicative of the value of the loss tangent. Comparison of field and laboratory data reveals that this technique is well suited for measurements of soils and snow. Mid to upper frequency values are best obtained by using a resonant cavity approach. While these cavities yield highly precise values for materials such as ice, rocks, and vegetation samples, they require the removal of the material from its natural position and possible machining for placement in the cavity. Shift in resonant frequency and the lowering of the cavity's Q value are related to the complex permittivity in the same manner as the coaxial resonator. It should be noted that the PDU is primarily a broad-band transmitter and detector capable of operating in both a CW or FM mode. This enables the unit to measure a broad range of materials as several measurement techniques can be accommodated by these modes. Further research into applying additional measurement techniques as well as calibrating this unit with selected reference dielectric materials is currently underway. Electrical and mechanical specifications of the ERIM portable dielectric unit are given in Table 4. A circuit diagram for the portable dielectric unit is shown in Figure 11.



$$\frac{\tan \frac{\omega}{c}(L - \Delta L)}{\frac{\omega}{c}\Delta L} = \frac{\operatorname{ctn} \frac{\omega}{c}\sqrt{\varepsilon}\,\Delta L}{\frac{\omega}{c}\sqrt{\varepsilon}\,\Delta L}$$

Figure 9. Coaxial Resonator Filled with Material of Unknown Dielectric Constant



$$\epsilon_r^* = \epsilon_r' - j\epsilon_r''$$

$$\epsilon_r' = \left(\frac{f_o}{f_s}\right)^2$$

$$\epsilon_r'' = \epsilon_r' \left\{ \frac{1}{Q_s} - \frac{1}{Q_o} \sqrt{\frac{f_s}{f_o}} \right\}$$

f_o = free space resonant frequency

f_s = filled cavity resonant frequency

$Q_o = f_o / \Delta f_o$

$Q_s = f_s / \Delta f_s$

Δf_o = bandwidth at f_o

Δf_s = bandwidth at f_s

Figure 10. Circular Resonant Cavity is Filled With an Unknown Material. The Dielectric Constant is Determined Using the Change in Resonant Frequency and the Q of the Cavity

TABLE 4
ELECTRICAL AND MECHANICAL SPECIFICATIONS OF
ERIM PORTABLE DIELECTRIC UNIT

Frequency Range:	400 MHz to 8.0 GHz
Resolution:	10 Hz from available frequency counter port
Sweep:	Manual
Mode:	CW or 1 KHz pulse modulation
RF Source:	6 individual VCOs with overlapping ranges
RF Output:	+10 dBm unleveled
Output Impedance:	50 Ohms nominal
Meter:	Digital display corresponding to output frequency
Power:	16 Amp-hour, 12 VDC rechargeable gel cells or external 110 VAC
Operating Time:	8 hours approx.
Recharge Time:	6 hours approx.
Dimension:	12" x 8" x 11"
Weight:	25 lbs (11 kgms)
Operating Temperature Range:	-10°C to +65°C

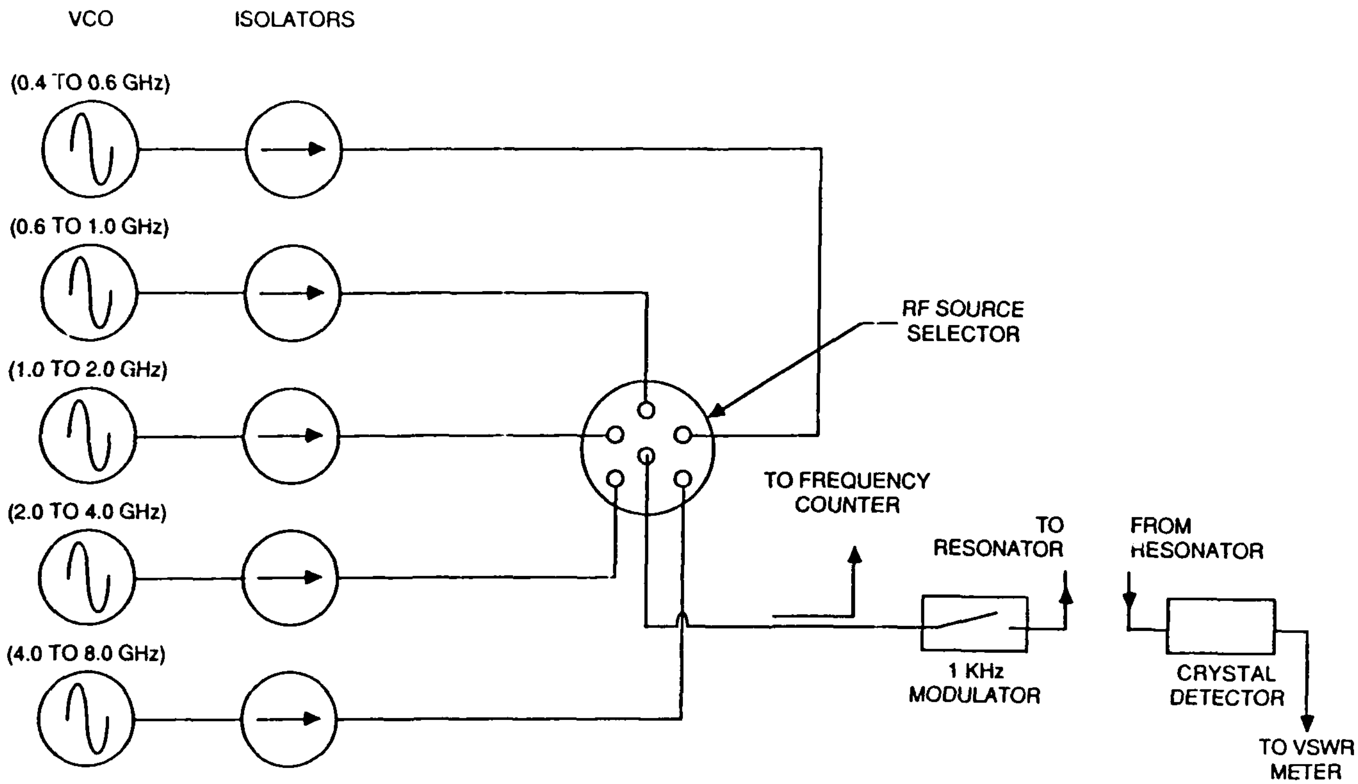


Figure 11. Circuit Diagram for the Portable Dielectric Unit